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ORBIT TRANSFER VEHICLE (OTV) ADVANCED EXPANDER CYCLE ENGINE POINT DESIGN STUDY. VOLUME 1: EXECUTIVE SUMMARY

Pratt And Whitney Aircraft Group
West Palm Beach, FL

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ORBIT TRANSFER VEHICLE (OTV) ADVANCED EXPANDER CYCLE ENGINE POINT DESIGN STUDY

EXECUTIVE SUMMARY

Contract NAS8-33567

Prepared for
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared by
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16

FOREWORD

This technical report presents the results of the Orbit Transfer Vehicle (OTV) Advanced Expander Cycle Engine Point Design Study. The study was conducted by the Pratt & Whitney Aircraft Group, Government Products Division of the United Technologies Corporation for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center under Contract NAS8-33567.

The results of the study are contained in the following three volumes which are submitted in accordance with the data requirements of Contract NAS8-33567:

Volume I — Executive Summary
Volume II — Final Technical Report
Volume III — Engine Data Summary

This study was initiated in December 1979 with the technical effort completed in eleven months. The study effort was conducted under the direction of the George C. Marshall Space Flight Center's Science and Engineering Organization with Mr. Dale H. Blount as Contracting Officer's Representative. The effort at P&WA/GPD was carried out under the directon of James R. Brown, Program Manager.

TABLE OF CONTENTS

SECTION 1
INTRODUCTION

The objective of the Orbit Transfer Vehicle (OTV) Advanced Expander Point Design Study was to generate the system design of a performance-optimized, advanced LOX/hydrogen expander cycle space engine. This engine is intended to be used in an OTV with an IOC date in the late 1980's.

The engine requirements that are emphasized by the OTV application include: high specific impulse within a restricted installed length constraint, long life, multiple starts, different thrust levels and man-rated reliability. Development and operational experience with the expander cycle RL10 engine, combined with our experimental work on high-pressure staged combustion rocket engines, led us to the conclusion that for upper stage space engine applications, selection of the expander power cycle would result in an engine that would be significantly cheaper to develop. Design studies on advanced engines for shuttle upper stage applications, that we carried out in the early 1970's, showed that the difference in specific impulse between advanced expander and staged combustion cycle space engines was less than 1%. This potential difference was too low, in our opinion, to justify the much greater development cost and risk of the staged combustion engine in this size.

In 1973, under Contract NAS8-28989, "Design Study of RL10 Derivatives," we designed the RL10 Category IV engine, a "clean sheet" update of the RL10 design concept, using the same expander cycle, but optimized specifically for the Space Tug. The engine requirements for the Full Capability Space Tug and those for the Orbital Transfer Vehicle, as specified in Section 2.0 of the Scope of Work (Engine Requirements), are very similar and are compared in the following:

2.0	OTV Engine Requirements (from SOW)	RL10 Category IV
2.1	Expander Cycle, with LH_2 and LO_2	Same
2.2	Engine Thrust 15K lb at MR 6.0:1	Same
2.3	Installed Length (two-position nozzle retracted) $\leq$ 60 in.	57 in.
2.4	1980 State of the Art	1973 State of the Art
2.5	MR Range of 6:1 to 7:1	MR Range 5.5 to 6.5:1
2.6	Fuel NPSH 15 ft Oxygen NPSH 2 ft	Fuel NPSH 0 ft Oxygen NPSH 0 ft
2.7	Life $\geq$ 300 firings/10 hr	Same
2.8	Chamber pressure spikes $< \pm$ 5%	Not specified
2.9	2-position contoured bell nozzle	Same

2.10 Gimbal range +15 deg pitch − 6 deg pitch ± 6 deg yaw	± 4 deg pitch ± 4 deg yaw
2.11 Engine provides H_2 and O_2 autogeneous pressurization	Same
2.12 Man-rated, provides abort return	Not specified
2.13 Meet Orbiter Safety Requirements	Same
2.14 Low Thrust Operation at ≈ 1K lb	Maneuver thrust at 3.75K lb

The impact of the differences in engine requirements, such as different inlet conditions, gimbal angles, mixture ratio range and low thrust level, is comparatively minor. An issue that will have to be addressed in conjunction with the Vehicle System Contractors is how the engine can assist in providing abort return of the vehicle.

The study objective calls for a performance-optimized engine system design. For a typical OTV mission, engine specific impulse has a far greater performance impact than engine weight (+1 sec Isp would justify > 40 lb increase in engine inert weight), so the emphasis was on maximizing specific impulse. Since engine cycle, propellants, nozzle concept, installed length, and mixture ratio are all specified, this is done primarily through increasing chamber pressure and hence nozzle area ratio.

A 15,000-lb thrust Advanced Expander Cycle Engine, that has been optimized to meet the study objective, is compared with the RL10 Category IV (1973) engine in the following:

	RL10 Category IV (1973)	*Advanced Expander Cycle Engine*
Thrust	15,000 lb	15,000 lb
Installed Length	57 in.	60 in.
Chamber Pressure	915 psia	1500 psia
Area Ratio	401:1	640:1
Isp at 6.0 MR	470 sec	482 sec
Weight	424 lb	427 lb
Life	300 firings/10 hr	300 firings/10 hr
Operation		
Full Thrust	Saturated Propellants	Low NPSH (2 ft O_2, 15 ft H_2)
Low Thrust	Saturated Propellants	Saturated Propellants
Conditioning	Tank Head Idle	Tank Head Idle
Technology	1973	1980

The most significant difference between these two engines is that the specific impulse of the Advanced Expander Cycle Engine has been increased to 482 sec. This 12-sec increase in specific impulse over the RL10 Category IV engine is due to a combination of factors which include: increased installation length (57 to 60 in.), updated performance prediction, use of the "preheat" expander power cycle, improved technology turbopumps with higher efficiencies, and reduced power margin.

Increasing the installed length of the 57-in. RL10 Category IV engine to 60 in. allows area ratio to be raised to approximately 433:1, increasing specific impulse by 1 sec.

Testing carried out subsequent to 1973 on engines with very high-area-ratio nozzles (i.e., RL10 with γ = 205, ASE with γ = 175 and 400) showed that the achieved performance was higher than that predicted by the current JANNAF methods by as much as 1.3%.

The chamber pressure of a power-limited expander cycle engine may be increased by preheating the chamber coolant with the turbine discharge flow, thereby raising turbine inlet temperature, and hence, increasing turbine power. This "preheat" expander power cycle was investigated on an improved version of the RL10 Category IV, the "RL10 Category IV*." Chamber pressure was increased by over 30% to approximately 1200 psia, giving an increase in specific impulse of approximately 1%.

Further increases in chamber pressure have been obtained by increasing turbopump efficiency through increasing speeds and by reducing turbine bypass flow. These higher speeds may require a considerable effort in the design of the fuel turbopump to prevent its operation at or below critical speed. Reducing turbine bypass flow from 5.7 to 3% reduces performance degradation margin, which may be undesirable on a long life engine. The effect of these changes is to allow chamber pressure to be increased by slightly less than 30% to 1,500 psia, giving an increase in specific impulse of approximately 1/2%.

Once the chamber pressure of an OTV engine is increased over 1,200 psia, the rate of increase in specific impulse with further increases in chamber pressure is quite low (approximately 1.3 sec/100 psia), and is decreasing, whereas the difficulty resulting from obtaining these further increases is high, and is increasing. It was not the purpose of this study to optimize performance gain vs development risk; rather, by maximizing performance in a point design of adequate depth, the key performance "driver" elements in an advanced expander cycle engine may be identified, thereby enabling the new technology requirements to be defined.

The schedule followed by Pratt & Whitney Aircraft during the performance of this study is shown in Figure 1-1. The interaction of the various design tasks is shown in Figure 1-2 and the results are summarized in Section 2 of this report.

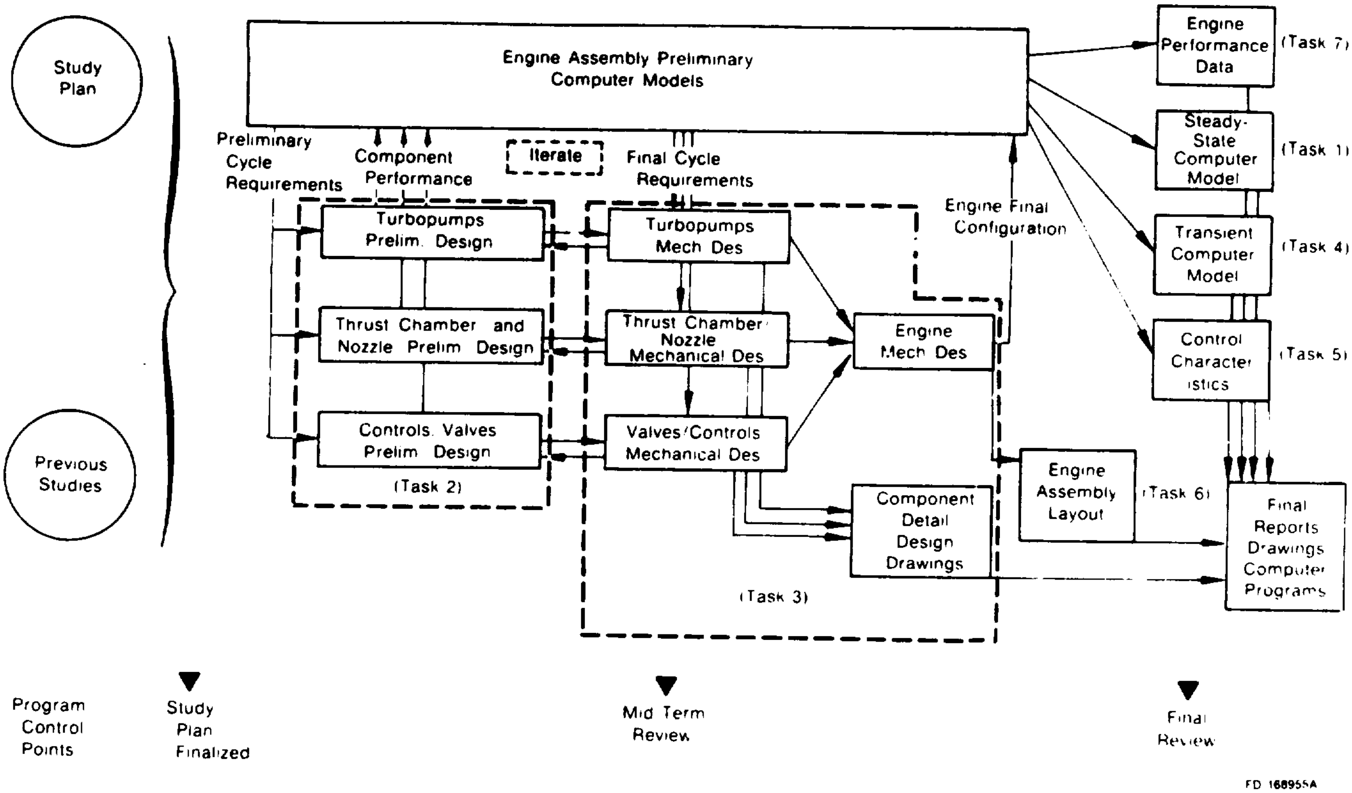


Figure 1-1. Study Flow Diagram

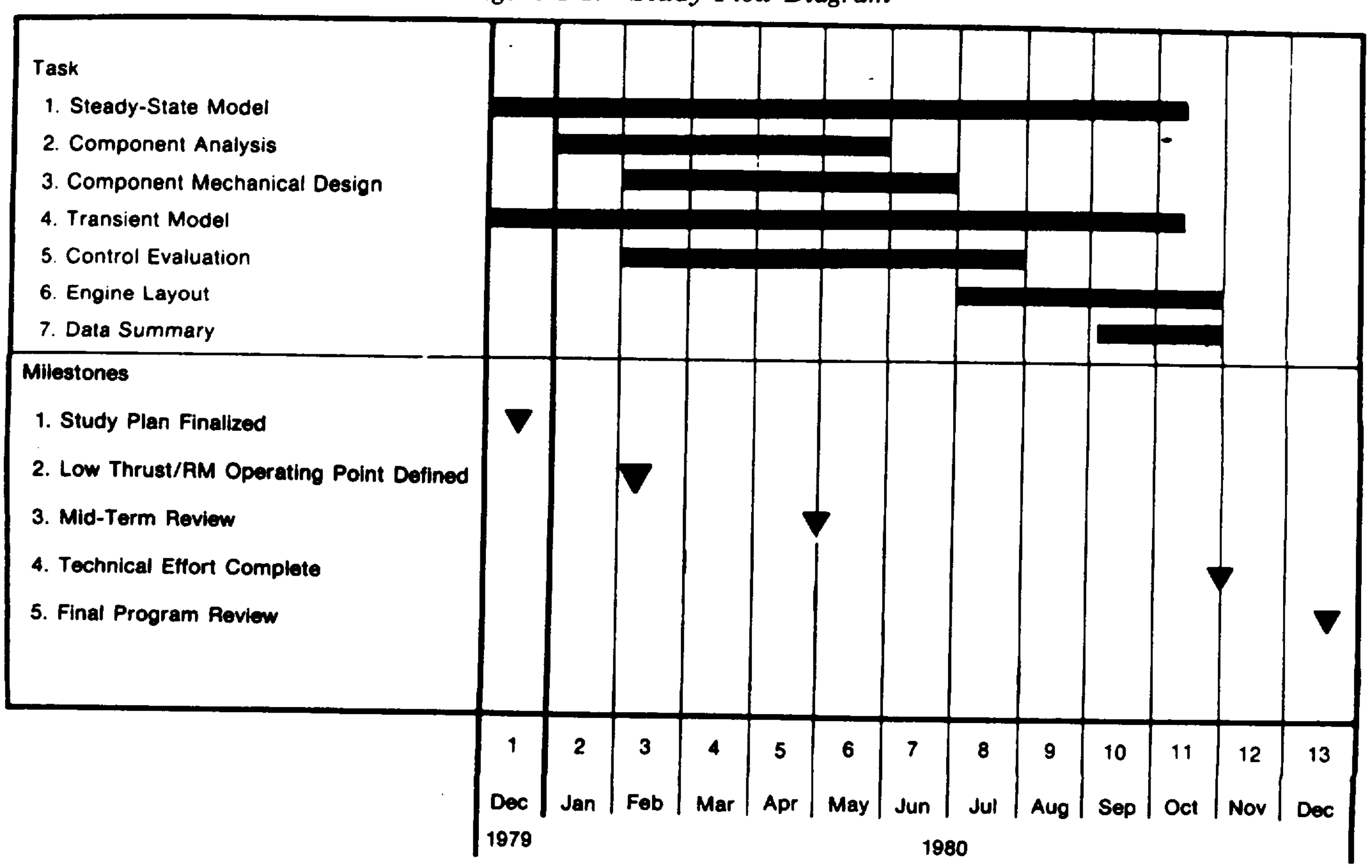
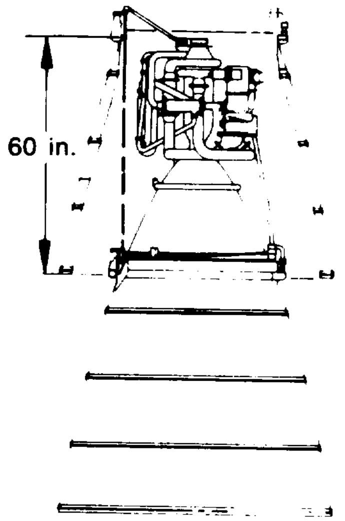


Figure 1-2. Advanced Expander Cycle Engine Point Design Study Schedule

SECTION 2
ADVANCED EXPANDER CYCLE ENGINE DESCRIPTION



Thrust	: 15,000 lb
Mixture Ratio	: 6.0:1 to 7.0:1
Chamber Pressure	: 1505 psia
Area Ratio	: 640
I_{SP}	: 482.0 sec at 6.0 MR
Operation	: Full Thrust (Low NPSH)
	: Pumped Idle (1500 lb Thrust) (Saturated Propellants)
Conditioning	: Tank Head Idle
Weight	: 427 lb
Life (Design TBO)	: 300 Firings/10 hr

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2.1 DEFINITIONS AND REQUIREMENTS

The Advanced Expander Cycle engine is a "clean sheet" advanced technology engine, incorporating improved pump and turbine designs and a hydrogen regenerator. Basically, it is a "1980 state-of-the-art" design optimized specifically for use in the man-rated OTV. The baseline Advanced Expander Cycle engine has the following requirements:

1. Interface requirements: not yet defined.
2. Operating modes:
   - Tank head idle
   - Pumped idle
   - Low NPSH pumping capability at full thrust.
3. Design life: 300 firings and 10 hr
4. Thrust level: 15,000 lb at 6.0 mixture ratio
5. Performance: optimized

2.2 DESCRIPTION

The general arrangement of the engine is shown in the installation drawing on Figure 2-1.

The principal components of the Advanced Expander Cycle engine are shown in Figure 2-2. The two-stage fuel pump is driven by a single-stage turbine. The fuel impellers are fully shrouded to obtain high efficiency. The single-stage oxidizer pump is driven by a single-stage turbine used in series with the fuel turbine. This was done so that the gears could be retained but the power transmitted through them could be reduced, leaving their stresses very low. By gearing the pumps and inducers together, control problems during transient operation are avoided.

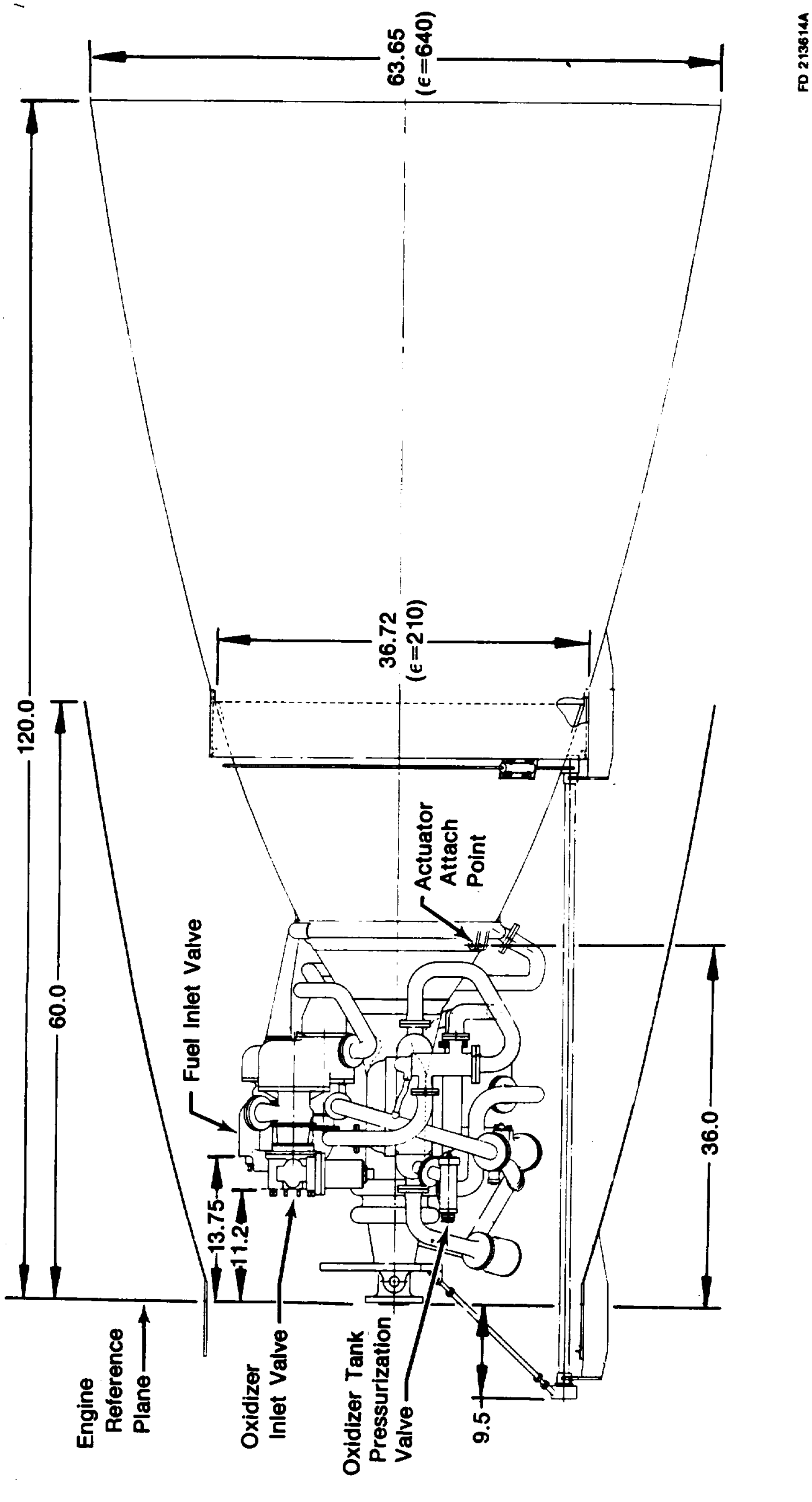

Figure 2-1. Advanced Expander Cycle Engine Installation

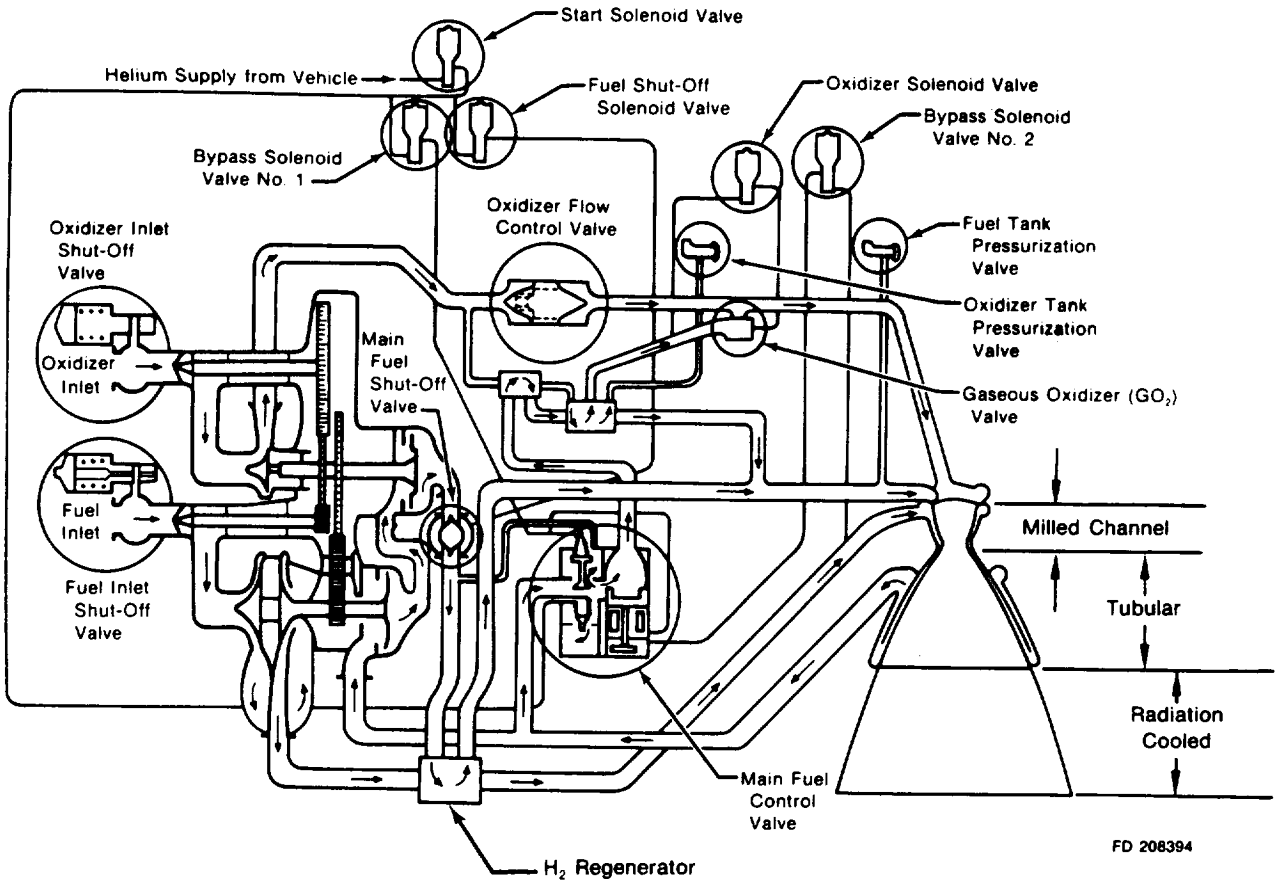

Figure 2-2. Propellant Flow Schematic Showing Location of Each Valve

Chamber pressure for the engine is 1500 psia, which is 600 psi higher than the RL10 Category IV engine. This increase in chamber pressure is obtained by utilizing "1980 state-of-the-art" turbomachinery design (i.e., fuel pump speeds ~ 150,000 rpm), and adding a hydrogen regenerator to increase turbine power. The hydrogen regenerator is inserted downstream of the fuel pump to increase the turbine inlet temperature by recovering heat downstream of the turbines and using it to preheat the fuel prior to cooling the thrust chamber and nozzle. The regenerator also allows a parallel chamber/nozzle coolant flow configuration to be used which, while providing adequate cooling, does not have the large pressure losses encountered in the manifolding of a counter-flow configuration. The milled channel thrust chamber has been designed and the tubular primary nozzle contoured to optimize the heat transfer characteristics anticipated by the engine at the high chamber pressure. A radiation-cooled, composite material extendible nozzle is used instead of a dump-cooled nozzle to provide a lighter, very simple system. Carbon-carbon, the composite material used, is a 1980 technology material currently used in high temperature applications because of its strength, light weight and high temperature characteristics.

A simple, reliable open-loop control system is utilized for the Advanced Expander Cycle engine. The valves operate in an open-loop mode for a passive control configuration, offering an advantage in both cost and reliability over an active control configuration. The engine operates with 3% bypass margin at the design point. Based on RL10 production engine data, this provides adequate margin for statistical deviations from nominal component operating characteristics.

The dry weight of the engine and its subassemblies are summarized in Table 2-1. Of the total engine weight of 427 lb, 70% is calculated and 30% is estimated.

TABLE 2-1. ADVANCED EXPANDER CYCLE ENGINE WEIGHT

Turbopumps and Gearbox	61 lb
Thrust Chamber and Primary Nozzle	101 lb
Extendible Nozzle Actuation System	20 lb
Extendible Nozzle	69 lb
H_2 Regenerator	33 lb
GO_2 Heat Exchanger	22 lb
Controls, Valves and Actuators	54 lb
Plumbing and Miscellaneous Hardware	67 lb
	427 lb

2.3 OPERATION AND PERFORMANCE CHARACTERISTICS

2.3.1 Operation

The operation of this engine during a typical start cycle is as follows. With the start solenoid and bypass solenoid No. 1 energized, thermal conditioning in tank head idle is carried out with the engine operating as a pressure-fed system without turbopumps rotating. After the pump conditioning has been completed (approximately 2 min required for an initial temperature of 500°R) the engine may be accelerated to pumped idle. By de-energizing bypass solenoid No. 1 and energizing the other two solenoids, the main fuel shutoff valve is opened and the turbine bypass in the main fuel control valve is first closed, diverting all the fuel through the turbines, and subsequently, as turbine inlet pressure builds up, reopened to allow the engine to stabilize at the pumped idle level. Also, as speed increases, the GOX valve opens further to adjust mixture ratio from 4:1 to 6:1 for pumped idle. De-energizing bypass solenoid No. 2 closes this bypass to a preset area accelerating the engine to full thrust. Opening the oxidizer solenoid valve allows the GOX valve to close as pump speed increases and the main oxidizer flow control valve opens just prior to GOX valve closure. Operation of the engine at full thrust and 6.0 mixture ratio is shown in Figure 2-3.

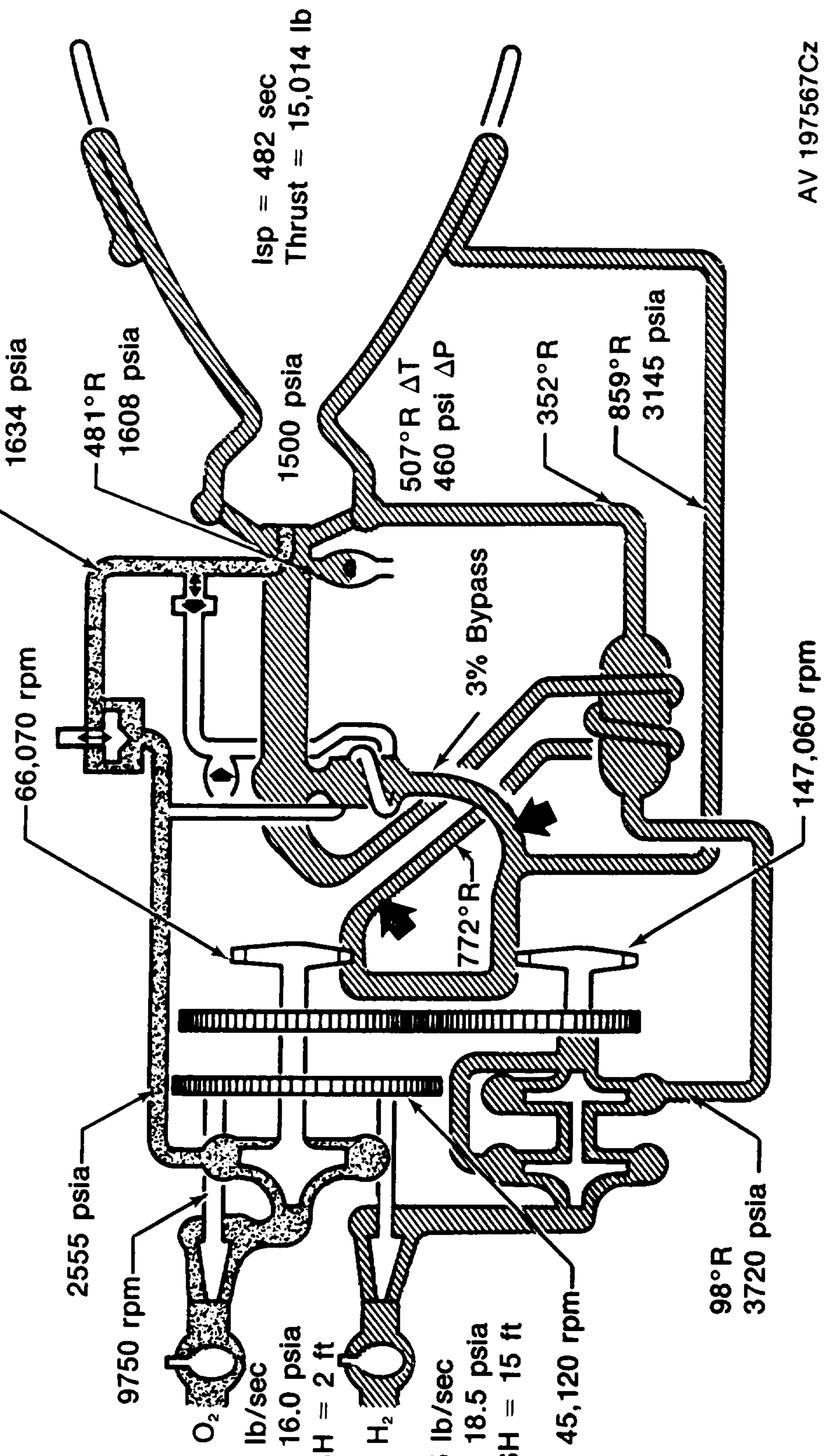

Figure 2-3. Advanced Expander Cycle Propellant Flow Schematic — Full Thrust (MR=6.0)

2.3.2 Engine Characteristics

The steady-state performance characteristics of the Advanced Expander Cycle engine are summarized in Table 2-2.

TABLE 2-2. STEADY-STATE PERFORMANCE CHARACTERISTICS OF THE ADVANCED EXPANDER CYCLE ENGINE

Operating Mode	*Tank Head Idle*	*Pumped Idle*	*Full Thrust*
Thrust, lb	72	1,500	15,000
Mixture Ratio	4.0	6.0	6.0
Chamber Pressure, psia	8.1	154	1500
Specific Impulse, sec	450	455	482.0
Fuel Turbopump Speed, rpm	0	37,000	147,000
Fuel/Oxidizer Pump Inlet Condition Limits	Superheated Mixed Phase or Liquid	0.0 NPSH	15 ft/2 ft

2.4 ENGINE DEVELOPMENT PROGRAM

No programmatic estimates were made under this contract. However, a program schedule was generated under NAS8-33444 for an engine of this type and the results are summarized here for reference purposes.

The total development program for the Advanced Expander Cycle engine requires 89 months of design, fabrication and test effort. This effort will encompass three design/build/test cycles to FFC. Figure 2-4 shows the total development program schedule and presents the major program milestones and key decision points.

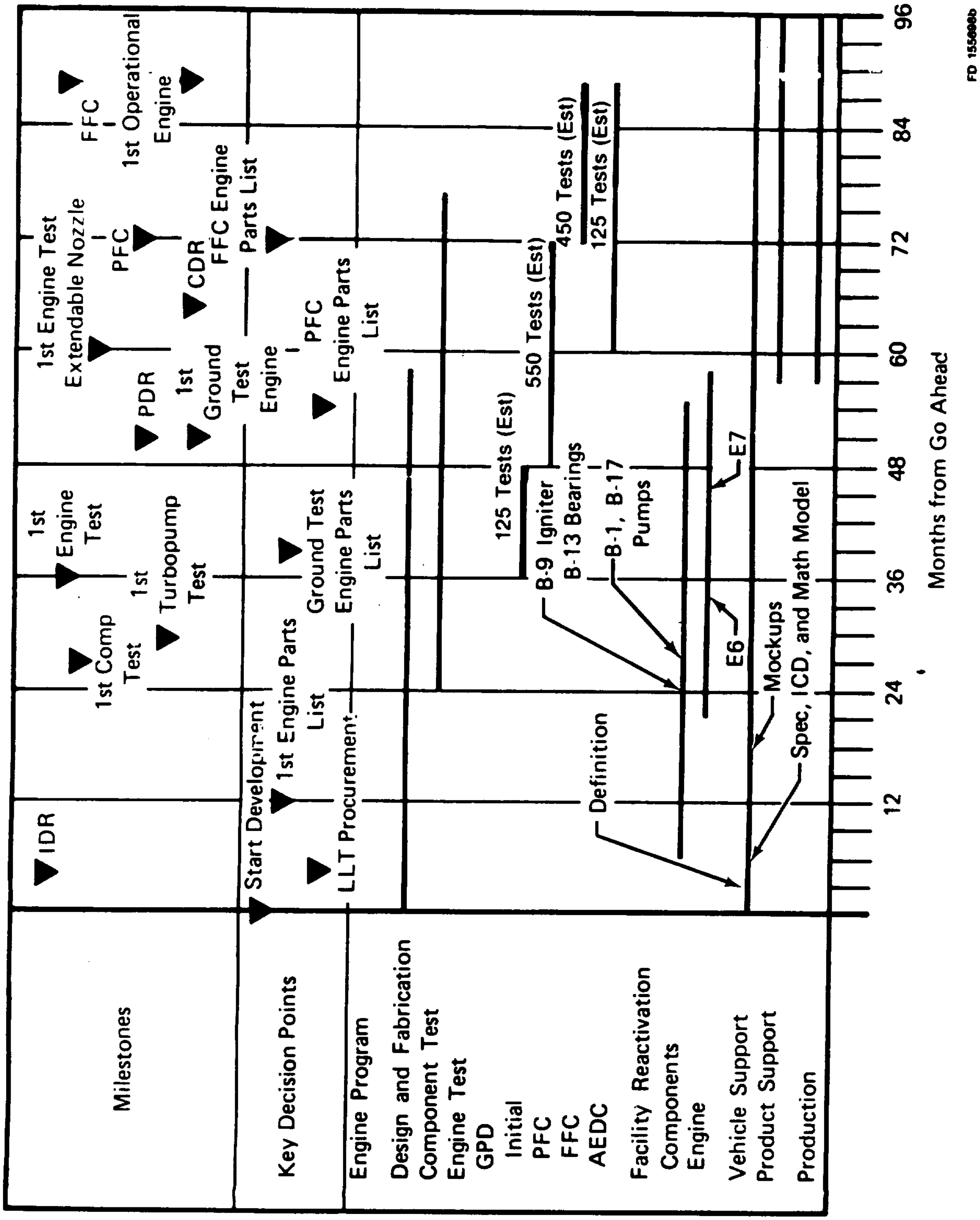

Figure 2-4. Advanced Expander Cycle Engine Development Schedule and Major Program Milestones

SECTION 3
CONCLUSIONS AND RECOMMENDATIONS

3.0 GENERAL

This study program has shown that an expander cycle engine can be designed which will provide very high performance for an OTV application. To proceed with confidence into a full-scale development program for such an engine, it is recommended that the following areas be addressed in future technology programs.

3.1 TURBOMACHINERY

3.1.1 Bearings

The 3.0×10^6 DN value used in this study for the fuel pump roller bearings is essentially at the limit of development. In order to attain higher pump speeds (and thereby increase pump efficiency) without incurring critical speed problems, other approaches in bearing concepts (such as improved roller element and case materials and hydrostatic journals) may be required. Rig testing is recommended for any concept prior to commitment in a development program.

3.1.2 Seals

The critical seal area for an engine of this type is the oxidizer pump seal package. While this engine design uses a controlled gap arrangement, it is believed that a high velocity rubbing bellows seal could be used provided that the oxidizer pump is properly balanced. If achievable, such a design would provide less leakage and thus better performance. A program to optimize controlled gap seals configurations for this application is also recommended.

3.1.3 Gears

The gear design of this engine uses a spur configuration. To improve load carrying capability which decreases wear (and thereby increases engine life) a helical gear, because of its increased contact area, might be considered. Improved coatings and/or case treatment for both spur and helical gears should be investigated. Since very little data is available on the characteristics of hydrogen-cooled gears, a technology program involving rig testing is recommended.

3.2 THRUST CHAMBERS

The design of the advanced expander cycle engine's thrust chamber using aged or half-hard AMZIRC appears to be adequate to meet the engine life requirements. However, the manufacturing of the convoluted wall design, while believed to be within the current state of the art, has not been demonstrated on hardware of this size. Also, progress made with electrodeposited coatings (e.g., ZrO_2) in recent years indicates a potential benefit for chamber low cycle fatigue (LCF) and for thermal enhancement. A subscale rig test technology program is recommended in this area.

3.3 MATERIALS CHARACTERIZATION

There are a great many new materials which are being used in various aerospace applications to improve durability. Unfortunately, few of the materials have been sufficiently characterized under the conditions imposed by the OTV engine design (e.g., hydrogen environment, cryogenic temperatures). Therefore, it is recommended that technology programs to investigate promising materials are studied. This effort should follow through sufficiently to provide potential users a "design practice" document so that a designer can utilize the new material as easily as a current material.

3.4 PERFORMANCE

It is probable that the OTV will depend on a very high area ratio nozzle to obtain the maximum possible specific impulse. To date, there has been very limited test data of hydrogen/oxygen combustion systems with high area ratio nozzles ($\epsilon > 175:1$) and none greater than 400:1. Since the test data was shown to disagree with the accepted JANNAF computer prediction of specific impulse by as much as 1.3%, and since the OTV engine may well use nozzle area ratio of $> 600:1$, the performance of such a nozzle should be verified. A technology demonstration is therefore recommended.